THE COSMOLOGICAL BARYON DENSITY FROM DEUTERIUM IN QSO SPECTRA

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The primordial D/H ratio now provides the best measure of the cosmological density of baryons. We describe in detail how we deduce the D/H ratio from absorption lines in the spectra of quasars, and we present our first two measurements of D/H in different QSOs, which agree to within the random errors. We describe how we correct D/H for blending with Lyman alpha forest H lines. For our two QSOs these corrections are small, because the D lines are narrow, deep and constrained by H and metal lines. The similarity of the two measurements rules out ad hoc astrophysical effects, such as the destruction of D without production of metals, or unusual data problems. We are confident that we have measured the primordial abundance of D (log D/H $= -4.62 \pm 0.05$), which is the first such measurement because other values in the literature are much larger, and apparently strongly contaminated. The implied baryon to photon ratio does not agree with the values predicted from measurements of ^{4}He or ^{7}Li. Since D is a simpler measurement and simpler astrophysically, we propose that there are large systematic errors with the ^{4}He data, and that ^{7}Li is depleted by a factor of three in halo stars. If this is correct, then we have the first measurement of the primordial abundance of any nucleon. We obtain a large value for the baryon density: $\rho = 4.4 \pm 0.3 \times 10^{-31}$ g cm^{-3} or $\Omega_b = 0.024 \pm 0.002h^{-2}$, such that 90% of baryons are unaccounted today. They are probably in the ionized intergalactic medium, and in the halos of galaxies, perhaps in some cases as condensed MACHO objects seen in gravitational microlensing events.

1 Significance of Deuterium

1.1 Why Measure D/H

The light nuclei deuterium (D or ^{2}H), ^{3}He, ^{4}He and ^{7}Li are created in big bang nucleosynthesis (BBNS). In the standard model their relative abundances depend on a single parameter: the ratio of the number density (cm^{-3}) of baryons to photons η. The ratio of any two nuclei gives a measure of η, but both D/H and ^{3}He/^{4}He are favored ratios for the following reasons. (1) These ratios are very sensitive to η. (2) They use isotopes of the same element, which should have nearly identical ionization, so that the observed ions are a good measure of the total of each element: e.g. D I/H I $\simeq$ D/H, where H I is the astrophysical notation for neutral hydrogen. (3) The abundance of D and ^{3}He are relatively high, unlike ^{7}Li. Deuterium has three additional advantages over ^{3}He: (4) All observed D is believed to be produced in BBNS, and there is complete destruction of D inside stars, so that observed D/H values will

be less than or equal to the primordial value. In contrast, stars both create and destroy ^{3}He. (5) The Lyman series lines of H and D lie at 912 – 1216Å , and are visible from space, or from the ground at redshifts $z > 2$, but the equivalent lines of He II are at 228 – 304Å and are hard to observe, even at high redshift from space, because photons of these wavelengths are absorbed when they ionize H I, which is very common both in our Galaxy and in the outer regions of other galaxies. (6) The Lyman lines of D are 82 km s^{-1} to the blue of those of H, where as the ^{3}He lines are much closer to (13 km s^{-1} to the red) those of ^{4}He.

1.2 Astrophysical Uses of High Precision D/H Measurements

There are six compelling reasons why we want to know the primordial D/H to high accuracy.

The baryon density is a fundamental cosmological constant. The density of photons in the universe is accurately know from the temperature of the cosmic microwave background, which has a Planck spectrum. The measurement of primordial D/H should then give the density of baryons at the time of BBNS, which is one of the few basic cosmological constants, like the Hubble constant H_0, the total density of matter Ω_0, and the age of the universe t_0. Baryons are one of the three most important constituents of the universe, together with the cosmic microwave background and non-baryonic dark matter. The baryon density plays a central role in the formation of the main structures in the universe: the intergalactic medium, galaxies, clusters, stars, as well as the production of metals and the release of heat and ionizing radiation.

The cosmological baryon to photon ratio depends on high energy physics, and may one day be calculated. The ratio of baryons to photons is set up prior to BBNS, possibly at the weak scale (e.g. in a first order phase transition) [6] or the GUT energy scales. When we know the appropriate high energy model it may be possible calculate this ratio, and hence the observed value of the ratio might be used to constrain parameters in the model, or to test models.

A precise value for Ω_b removes a degree of freedom from cosmological models. Prior to the measurement of D/H in QSOs, the ratios of the abundances of the different elements allowed about a factor of five range in the density of baryons. Our QSO data reduce the random error to 12%, a huge improvement. This type of precision is a powerful tool to advance cosmology. When we learn the value of a basic parameter, we remove a degree of freedom which previously helped models fit the data. We should get more powerful tests and more realistic models.

We can determine the fraction of baryons which are missing. Comparison of an accurate value for the baryon density at BBNS with counts of local baryons shows that $\sim 94\%$ are now unaccounted, enough to account for dark matter in galaxy halos. Alternatively, if the baryon density was low, few if any would be missing, and there would not be enough for galaxy halos, which would have to be non-baryonic.

Comparison of the primordial abundances of the light elements is a powerful test of the physics in BBNS. The abundances of all light elements should be consistent with a single value of η, and the value of the test depends on the accuracy of the abundances.

The changes in D/H with time help specify Galactic chemical evolution. The ratio of our D/H value, which is probably the primordial value, with the value in the local ISM shows that 0.67 ± 0.09 of atoms in the ISM have not been in stars. This value helps determine parameters which summarize galactic evolution, including the mass locked up in stellar remnants and long lived stars [5].

2 Deuterium in QSO Spectra

Deuterium is a fragile nucleus which is readily converted into ^{3}He and heavier elements in stars. The amount of D remaining in the local interstellar medium depends on the history of chemical evolution. Edmunds (1994) has shown that the fraction of primordial D remaining in the ISM should be ≥ 0.5 – 0.7, which is the fraction of (H) atoms in the ISM which have not been inside stars. This limit remains true for arbitrary inflow and outflow, and rules out high primordial D/H, but the precise numerical value depends on the fraction of mass which is not returned to the ISM, and on the ratio of gas to total mass.

Deuterium in QSO absorption systems should be closer to the primordial value, because most absorbers are in the far outer parts of galaxies or in the intergalactic medium, far away from most normal stars. Many absorbers are known to have low metal abundances, 0.01 – 0.001 of the solar value. This implies that a negligible amount of D will have been destroyed, because the gas ejected by stars which lacks D will contain metals.

Adams (1976) [1] discussed the two main requirements for the detection of Lyman series absorption lines in QSO spectra. First, we need an absorber with a lot of H I: a column density N(H I) $\gtrsim 10^{17}$ neutral H atoms cm^{-2}, large enough that the D I lines will be visible for D/H $\simeq 10^{-5}$. These N(H I) values are also large enough that the gas is partially or completely optically thick to Lyman continuum radiation: photons with wavelengths $\lambda < 912$Å (in the rest frame of the gas) ionize H I to H II, and are absorbed, producing a drop in the

QSO spectrum at $\lambda < 912$Å. These absorbers are called Lyman Limit Systems [16], and are readily identified in even low resolution spectra because they have a sharp drop at the Lyman edge. Second, the H I in the absorber must have a very restricted range of velocities, to avoid doppler motions which would cover the D line, 82 km $s^{-1}$to the blue of H. Most Lyman Limit systems do not show deuterium because the H absorption is seen over a wide range of velocities, including those where the D line would appear. Either the gas has too large a velocity of dispersion (high temperature, and/or large turbulent motions), or there are several absorbing gas clouds at slightly different velocities. In most cases there is enough H to absorb all the QSO flux at the expected position of D.

The line of sight to a QSO at $z \simeq 3$ intercepts about 6 absorbers with sufficient H I, but only about one of these will be at high enough z to shift the Lyman lines into the optical, where we can use large ground based telescopes.

Over the last 5 years we obtained medium resolution spectra of over 47 QSOs with the Lick observatory 3-m telescope to search for Lyman Limit systems with low dispersion velocities. We applied three criteria to the Lick spectra to find systems which might show D. An ideal system should have a sharp Lyman limit, a Lyman-α line with a small rest frame equivalent width W(Lyman-α) < 1 Å, and weak metal lines [16,8]. The sharp Lyman limit is only possible if there is residual flux between the high order ($n \simeq 15$ – 20) Lyman lines, which requires that those lines are weak, with low equivalent widths. This requires that the H absorbs over a narrow range of velocities (low T, small turbulent velocities, and absence gas clouds at different velocities) – exactly what we need to see D. The Lyman-α line must be weak if we are to see D and weak metal lines are an indication that the gas comes from a restricted range of velocities. (We might occasionally see D in an absorption system which has a strong Lyman-α line, but only if most of the H happens to be on the D side of the line, just far enough away to avoid covering the D line.)

We have observed 15 candidate systems with the 10-m W. M. Keck Telescope, and 2 have yielded deuterium measurements. These 15 were selected from about 77 QSOs, including 30 with published medium resolution spectra. The fraction of QSOs at $z \simeq 3$ which show D in optical spectra is about 3%.

Several papers have presented upper limits on D/H in QSO spectra [14, 3, 12, 18], one paper gives a lower limit [4], and one paper promotes an upper limit to a detection [11]. We now discuss our measurements on two QSOs, which are the only likely detections, and then we discuss the other QSOs.

3 D/H Towards QSO 1937−1009

Our detection of D in this QSO was described by Tytler, Fan & Burles [17]. High quality Keck spectra show strong absorption at the expected position of the D Lyman-α line and weak but highly significant absorption at D Lyman-β at a redshift $z_{abs} = 3.572$. All the weak metal lines at this redshift, C II, C IV, Si II, and Si IV, appear to have the same profiles, which are adequately described by two components separated by 15 km s^{-1}. The velocity positions determined from the metals (Figure 1) lie in the cores of the higher order Lyman lines, and show the expected positions of the deuterium absorption features. The Lyman lines show that $> 90\%$ of the H I must be in, near, or between the two components, but not elsewhere because there are no other lines in the spectrum which can explain the Lyman limit. A simultaneous fit to the two components gives a total column density log N(H I) = 17.94 ± 0.05. An additional component at $v \simeq +49$ km s^{-1} produces S IV, C IV and H I absorption, but it is absent from the high order Lyman lines. It has a low column density of log N(H I) = 14.94 ± 0.14, and it can not change D/H. The total D in both components is log N(D I) = 13.30 ± 0.04, which is fairly insensitive to the velocity dispersion and the precise velocity of the D because the D lines are unsaturated. We then have log D/H = −4.64 ± 0.06, where this error includes random photon noise, and fitting errors, but not systematic errors, which are discussed in Tytler, Fan & Burles [17].

3.1 Gas Temperature and Turbulent Velocity Dispersions

Absorption line widths are determined by three factors. Instrumental resolution (known from calibration data to be 8 km s^{-1} FWHM), turbulent (bulk) motions, and doppler broadening from thermal motions. Keck spectra have sufficient signal to noise ratio (SNR) to separate these last two. Turbulent motions effect ions of all elements equally, but thermal broadening depends on the mass of the element, because of equipartition of energy in the gas: light elements move faster. We have determined the temperature T, and turbulent velocities b_{tur} of the gas which shows D [17,2].

If Figure 2 we plot intrinsic velocity dispersion (observed, corrected from instrumental resolution) as a function of the mass of the ion, where $b \equiv \sqrt{2}\sigma$ is the velocity dispersion. The best fits for T and b_{tur} were determined without considering D. Note that the b values for D (the second data point from the left in each top panel) are very close to the expected value shown by the curves. This must be the case if our model is a good fit to the data, and the agreement provides additional evidence that the lines are D and not some other ion.

The sound speed in the gas [15], $c = \sqrt{kT/\mu}$, given in Table 1, and are 10

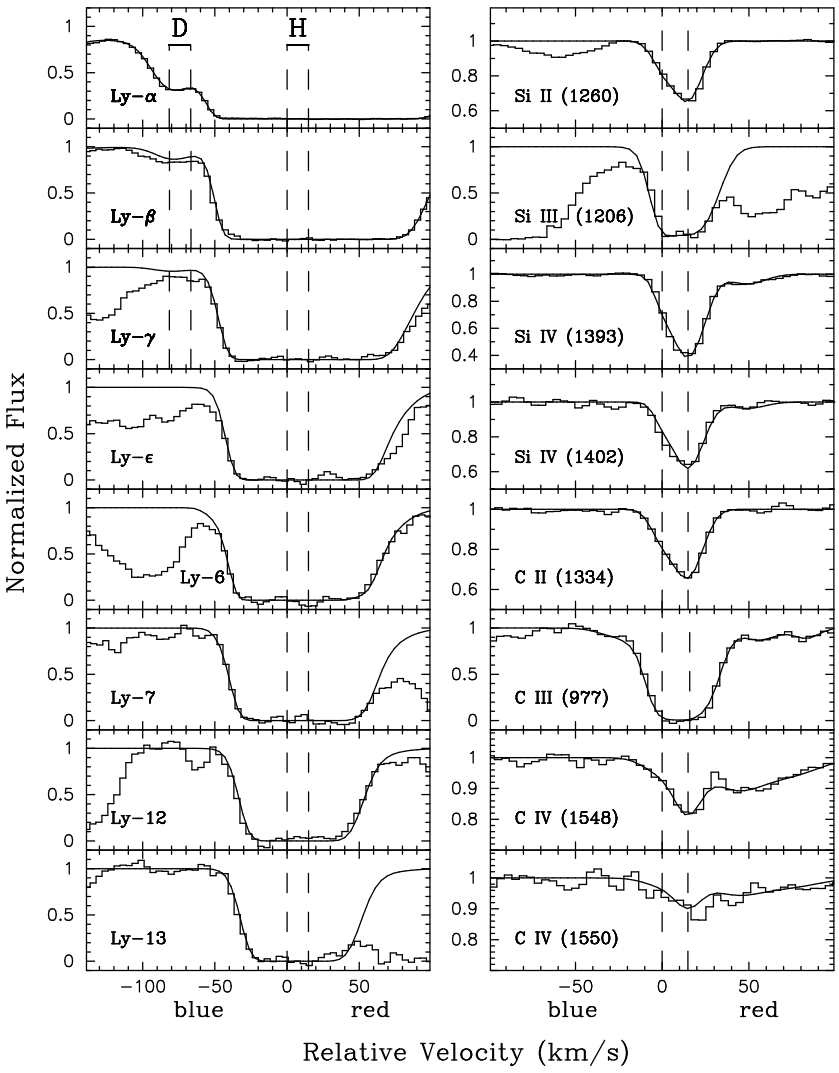

Figure 1: Spectrum of absorption lines in QSO 1937–1009. The Lyman series lines (left), and the metal lines (right) arise in the same gas. The velocity scale is relative to the redshift $z = 3.572201$ of the blue component (smaller wavelength). The red component at $z = 3.572428$ is indicated by a second dashed line at $+15$ km s^{-1}. The histogram represents the observed counts of the combined Keck spectra in each pixel, normalized to the quasar continuum. The smooth curve shows the Voigt profiles convolved with the instrumental resolution which produces the best simultaneous fit to all the lines.

– 12 km s^{-1}, where the mean molecular mass $\mu = 1.22\times$ mass of the proton. With thermal broadening, $b = \sqrt{2kT/m}$, thus we can equate b_{tur} to $\sqrt{2}c$, to find that the turbulence is subsonic and quiescent, since the four clouds have b_{tur} = 2.3, 3.2, 4.8 and 8.4 km s^{-1}. If $b_{tur} > \sqrt{2}c$ the turbulence would have been be supersonic, and we would expect an energy source which would set up shocks which create variations in the density and temperature.

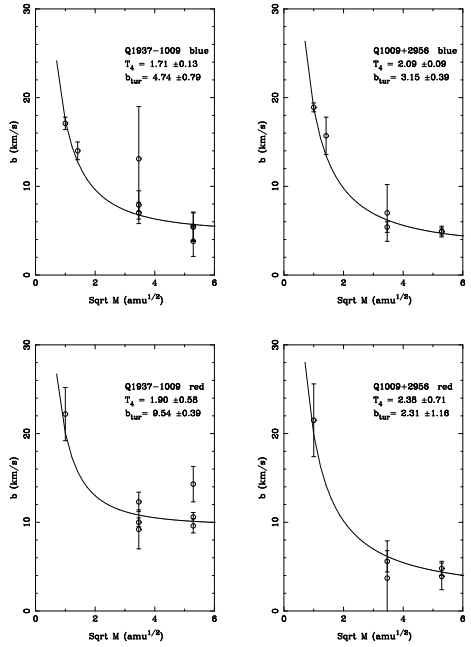

Figure 2: The intrinsic velocity dispersion (observed b, corrected for instrumental resolution) as a function of the square root of the mass of the ion, in atomic mass units. The ions shown are H, D, C and Si. We do not show D in the red components (lower panels), because b(D) can not be measured in those components, which are blended on both sides, with the blue components of D and H. The b_{tur} is the asymptotic level of the curve running to the right, where thermal broadening is negligible for high mass ions. The steepness of the rise in b to the left is a measure of the gas temperature, where $T_4 = T/10^4$ K.

3.2 The two gas clouds seen in QSO 1937−1009

The absorption system to QSO 1937−1009 which shows D is extremely unusual because it has only two main components, but it has a large N(H I) $\simeq 10^{18}$cm^{-2}. Typically we would see 5 – 10 components in spectra with high

SNR and high spectral resolution, one or more of which would cover up D, which is why D is hard to find.

The two components, which are a sufficient description of the spectral lines, can have two different origins: a single gas cloud with a range of metal abundance and asymmetric (non-Gaussian) turbulent velocity distribution, or two unrelated gas clouds.

First, with one gas cloud, the distribution of turbulent velocities would mimic the b values found in the two components fit to H. If the different elements and ions are well mixed, then all absorption lines would have the same velocity distribution, but the spectra show that this is not true. In Figure 1 we see that the D line is deepest in the blue component, but the metals are deepest in the red. The H I is mostly (63%) in the blue component, which contains only $\simeq$ 20% of the metals ions. The metal abundances are about 7 times higher in the red component. We can have either a gradient in abundances in a single, unmixed clouds, or two separate clouds. The sound crossing times in the clouds, $t_c = L/c$, are given in Table 1. For the two clouds in QSO 1937−1009 they are 0.6 and 1 Gyr, long enough that the gas may not be mixed. For the single cloud there could be two streams of gas mixing in the same space.

Second, there could be two gas clouds, which could be completely unrelated. The physical separation corresponding to 15 km s^{-1} radial velocity could be $d_{sep} = v_{sep}/H(z) = 30-50h^{-1}$kpc, from Hubble flow velocities alone, depending on the cosmology. While the two components need not be physically associated, we speculate that they are tens of kpc apart in the outer halo of a galaxy.

The small velocity difference between the two components is compatible with gas in a galaxy halo. Velocity dispersions in halos today are hundreds of km s^{-1}, but much smaller velocities will be the rule for D, for two reasons. First, absorption systems are so common that very few can come from the inner parts of galaxies. Relative velocities will be less in the outer parts of halos, especially for gas which has not yet fallen in, which will be common at high z. Second, relative velocities must be small for D/H systems ($\sigma < 14$ km s^{-1}) because they were selected to not have gas over a large range of velocities. Deuterium could not be seen otherwise.

The difference in the abundances of the two components is not a surprise. At early times, and in the outer regions of galaxies, there would be a large dispersion in abundances in gas which had not mixed.

Table 1: Properties of Gas which shows Deuterium.

QSO cloud	N(H I) (log)	T_4^a (K)	b_{tur} (km s^{-1})	$2^{1/2}c$ (km s^{-1})	L (kpc)	t_c (Gyr)
1937 blue	17.74	1.62	4.8	14.4	11	1.1
1937 red	17.50	2.36	8.4	17.4	7	0.6
1009 blue	17.36	2.1	3.2	16.4	5	0.4
1009 red	16.78	2.4	2.3	17.5	1	0.08

$^a T_4 = T/10^4$ K. Values and their errors are derived in Tytler, Fan & Burles (1996) and Burles & Tytler (1996)

3.3 Why the Data on QSO 1937−1009 do not allow a High D/H

We would need to increase N(D), or decrease N(H), neither of which is possible. If we increase N(D) we would see dramatically more absorption. The D line is unsaturated, absorbs about 0.7 of the flux in its core, and is seen in data with SNR 75 per pixel of 4 km s^{-1}. It extends over > 10 pixels in Lyman-α and it is also seen in Lyman-β . The 1 σ uncertainty in N(D) is 10% ([17]), so a ten fold increase is ruled out at the 70 σ level. Adding contaminating H to the D line acts in the wrong direction; there is then less D, and a lower D/H.

The situation with H is as tight [17]. The 1 σ uncertainty in N(H) is only 12%, which is precise for several reasons which do not apply to most other absorption systems which have been analysed in the past. It is incorrect to generalize that we can not obtain accurate N(H I) whenever H lines are saturated. (1) We have high SNR and high resolution. (2) We have done a simultaneous fit to 13 H lines and the Lyman continuum. The oscillator strength of Lyman-19 is 2000 times smaller than that for Lyman-α which means that their absorption lines profiles are significantly different, which gives sensitivity to N(H I) even when lines are saturated. Lyman lines 12 – 18 are clearly seen and resolved, and give log N(H I) $= 17.7 \pm 0.07$, with a 2σ limit at 17.94, which is the best fit to all the Lyman lines. (3) The Lyman continuum absorption also requires a high log N(H I) > 17.8. We have looked for other absorption systems in the spectrum which might account for this Lyman continuum absorption. There are none, and all of the absorption comes from the system which shows D. (4) Adding a third or fourth component will not change the answer significantly, as long as their redshifts coincide with the metal lines.

We know that the continuum near 4180 Å is well determined because the fit to the Lyman lines is good, and there is little absorption between the Ly-series. The SNR weighted flux in the region 4125 - 4175 Å is 0.015 ± 0.014, where the continuum level is 1.0, which corresponds to an optical depth of $\tau > 3.5$ (1σ) and log N(H I)> 17.74.

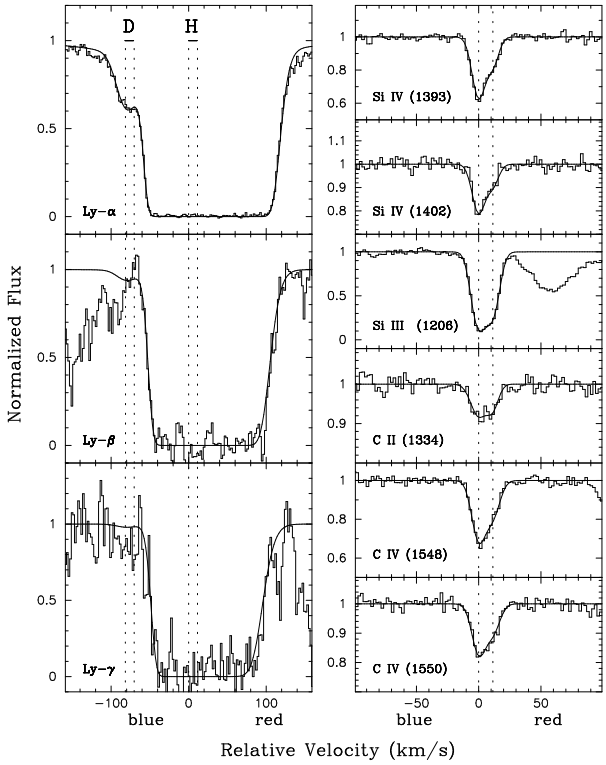

Figure 3: As Figure 1 but for QSO 1009+2956 (emission redshift $z_{em} = 2.616$, V=16). Keck spectra of Lyman α, β, γ (left), and all the metal lines (right) in the absorption system. Zero velocity corresponds to the redshift $z = 2.503571$ of the blue component. The red component at $z = 2.503704$ is indicated by a second dashed line at +11 km s^{-1}.

Models which give a higher D/H by lowering N(H I) must leave residual flux below the Lyman limit, unless the H is put in other absorption systems. We stated in Tytler, Fan & Burles (1st sentence in 4th paragraph) that all the H must lie in the main absorption system, because the Keck spectrum of the Lyman-α forest shows that there are no other absorptions systems with large

N(H I) in this region. To the blue of the D/H absorption system (z = 3.572), the only moderate column density systems are (z = 3.555650, log N(H I) = 15.06, b = 27), (z = 3.553659, log N(H I) = 15.11, b=53.8), and (z = 3.256067, log N(H I) = 15.70, b= 36.0). These systems do not have enough N(H I) to have a noticeable effect on the flux blueward of 4180 Å hence all of the H I which causes the Lyman break is in the D/H system.

We conclude that there is no possibility that D/H is much larger than we stated. Continuum errors could systematically increase log D/H by 0.06 (15%), but not much more.

4 D/H Towards QSO 1009+2956

In Figure 3 we show nine lines in the absorption system at $z = 2.504$ towards QSO 1009+2956. Details are given in Burles & Tytler [2]. The residual flux below the Lyman edge gives an accurate and independent measure of all H I in this velocity region [2], log N(H I) = 17.46 cm^{-2}. There are no other Lyman-α lines within 5000 km s^{-1} of $z = 2.50$ which have H I column densities $> 10^{16}$ cm^{-2}, so that all of the Lyman continuum absorption must be produced by gas in the $z = 2.504$ absorption system. The blue side of the Lyman-α , Lyman-β and Lyman-γ lines are best fit if all of this H I is near the two velocity components which are seen in the metals. There could be be additional H at velocities between the metal lines and +40 km s^{-1}, provided this gas has very low metal abundances [C/H] < -3.5. But, nearly all known QAS with large N(H I) have metal abundances [C/H] > -3. A simultaneous fit to the Lyman α, β, and γ lines in the Keck spectrum and the Lyman continuum absorption in the Lick spectrum (Figure 3) gives D/H = $3.0\,^{+0.6}_{-0.5} \times 10^{-5}$ (1σ random photon and fitting errors).

4.1 The two gas clouds seen in QSO 1009+2956

Unlike QSO 1937−1009, for QSO 1009+2956 the metal and D lines have the same velocity profiles, so that the two velocity components have the same metal abundances. This rules out mechanisms which might separate metals from D and H. For this QSO it is more likely that the two components could be part of the same gas cloud, which has an asymmetrical distribution of turbulent velocities. The blue component has 80% of both the H and metals.

4.2 Why the Data on QSO 1009+2956 do not allow a High D/H

The random error on N(H I) is 12%, while that on N(D I) is 15%, both very small. The 1σ error on D/H is 0.5×10^{-5}, so that D/H $\simeq 25 \times 10^{-5}$ is ruled

out at the 50σ level. A larger D/H would require a much lower N(H I), which is ruled out by the Lyman continuum absorption. Again, there are no other Lyman-α lines in the spectrum which can account for this absorption. We conclude that D/H must be low in this absorber.

5 Detections – Not Upper Limits

A major difficulty with the measurement of D/H is that there is additional H absorption at a large fraction of wavelengths where D could be seen, which is always in the Lyman alpha forest. This additional H can blend with real D lines, it can completely swamp the D line so that the signal is mostly H, it can produce a saturated line with no remaining flux in the core, and it can change the H lines which are associated with the D.

For our two QSOs the main effect will be slight increases in the amount of absorption at the position of D. There will not be any noticeable change to N(H I) because we see many H lines, we reject those which are blends (absorbed more than expected) and we see Lyman continuum absorption.

We used Monte Carlo simulations of spectra [17] to estimates the amount of H absorption on top of the D, and we have corrected our D/H values for this additional H. The corrected D/H values are then measurements and not upper limits.

In Figure 4 we show the log likelihood as a function of D/H. For each D/H we made a template spectrum showing the D and H Lyman-α lines, where all parameters are fixed by the T, b_{tur} and z values given in Table 1. We made 500,000 template spectra for each D/H, and to each we added different Lyman-α forest lines selected at random from known distributions of N(H I) and b (a Gaussian centered at b=28 with $\sigma = 6$ km s^{-1} and no values with $b \leq 12.5$). The likelihood is calculated comparing each template with the Keck spectrum. For QSO 1937−1009 the most likely D/H is only slightly lower that the value obtained by fitting the data, but for QSO 1009+2956 the most likely D/H is lower than the fit value by about 1σ.

The likelihood plots show that there is a negligible chance that the D line in QSO 1937−1009 is significantly contaminated by H from the Lyman-α forest. There are three reasons why a combination of one or more H I lines can not reproduce even a small portion of the column density at the position of D. First the D line is deep – it absorbs 70% of the flux in its core – and it would require lines with large N(H I) to match this absorption. Such lines are rare. Second, the line has a very steep blue edge, which requires a low b value. Even if D/H in the two components is at the ISM value, and additional H at some near by velocity accounts for most of the absorption where D is expected, we

find this contaminating H would have $b < 18$ km s^{-1}, which is low enough to be unusual. Very few H I lines are this narrow, especially at high N(H I). Third, the SNR is high, 75 per 4 km s^{-1}pixel, and D extends over > 10 pixels, which means that the fit must be extremely good to get a large likelihood that the data comes from the model.

But for QSO 1009+2956 the likelihood plots show that we should expect some H on top of the D. This is because this D line is not as deep (it absorbs 0.4 of the flux in its core), and it is not as steep as the D line in QSO 1937−1009: the errors now permit a larger b: 15.7 ± 2.1 km s^{-1} versus 14.0 ± 1.0.

The chance of contamination will be much larger in data with lower SNR or lower spectral resolution, or when fits are poor or non-unique, because we are then less able to distinguish between a D profile, and a blend of H lines which appear similar. Lines with large b (similar to Lyman-α forest lines), and low N(H I), (most forest lines have low N(H I)), are also most likely to be contaminated with H.

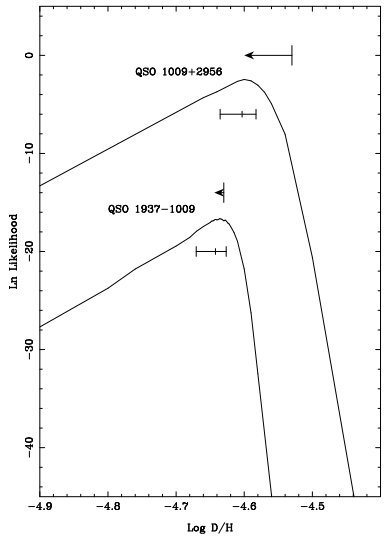

Figure 4: Natural Log Likelihood as a function of D/H in our two absorption systems. The arrows show the shift in the expected value of D/H when contamination from weak Lyman-α lines is removed. The error bars show the means and standard deviations of the likelihood functions. The normalizations of the likelihood functions are arbitrary.

5.1 D/H could be Lower: Blending with H in the Lyman limit system

We have described the statistical correction of D/H for unrelated Lyman-α forest lines at the location of D. This simulation does not correct for H which is statistically or physically associated with the gas which showed the D. Such H could lie on top of the D line, and increase the measured D/H above the true value. It would not effect N(H I) unless its column density was comparable to the main components, in which case it would have been detected.

We can not simulate such correlated gas, because we do not how it is distributed. We need the distribution in velocity (two-point correlation function) on scales down to 40 km s^{-1}, and the distribution in T, b_{tur} and metal abundances (metals would be seen if present – ruling out contamination of D) of all H I in absorption system complexes with total N(H I) comparable to those which show D. This data will be difficult to obtain because, (1) the H lines are normally strongly blended, and (2) we will need to observe tens of systems to see if the distributions are same for all types of systems, e.g. those with different numbers of components, or different total N(H I). This is important because the gas which shows D is not a random sample of Lyman limit systems. They were pre-selected to be suitable for the detection of D: steep Lyman breaks, weak H and weak metal lines, which together imply few velocity components, low temperatures, and low b_{tur}.

If there are differences, then we may have to limit the sample to those systems which show D, which means that we will have many D/H measurements before we can make corrections for associated H.

We can use the red side of an absorption system to determine the properties of the associated H, because the red and blue sides in many different gas clouds will be statistically identical except for the D in the blue. For both our systems there is one additional low N(H I) absorbing component on the red. For QSO 1937−1009 this extra component has $b = 33.5$ km s^{-1} at $v = 49$ km s^{-1}, and for QSO 1009+2956 the extra component has $b = 31$ km s^{-1} at $v = 40$ km s^{-1}. These two cases show that the associated gas does not necessarily have a low b value, and in neither case could this gas look like or contribute significantly to the D lines, which have much smaller $b(D) \simeq 15$ km s^{-1}.

5.2 What if the two clouds have different D/H?

For QSO 1937−1009 and QSO 1009+2956 we could not measure the z, N(H I) or b values for D in the red components because they were blended on both sides, with the blue components of H and D. Some absorption is required here to account for the spectrum, so we set $(\mathrm{D/H})_{red} = (\mathrm{D/H})_{blue}$. If we relax

this constraint, for QSO 1009+2956 we find for the blue component: N(H I) $= 17.3 \pm 0.9$, N(D I) $= 12.94 \pm 0.05$ and log D/H $= -4.4 \pm 0.9$. Here N(H I) has gone down 15%, N(D) up 26% and D/H up 32%. But the random error on D/H is now a factor of 8, rather than 20%. For the red component N(H I) $= 16.6 \pm 8.2$, N(D I) $= 12.0 \pm 0.3$, and log D/H $= -4.6 \pm 8.2$. Huge errors. We get much smaller errors when we add the constraint that the total H and D must together match the spectrum. One way to introduce this constraint is to take D/H down to the ISM value in the red component, and conserve the total D by increasing D in the blue component. For QSO 1937−1009 we get $(\mathrm{D/H})_{blue} = -4.57$, which is still a low value. A second way is to tie to have the same D/H, as we did in our analysis [17,2].

6 Size and Mass of the Absorbing Clouds

6.1 Length down the line of sight

We can calculate the length of the absorbing gas by dividing the column density of neutral hydrogen by its estimated number density, $L = N(H\ I)/n_{H\ I}$. The column densities are well specified by the optical depths at the redshifts of the absorption systems. In our two systems we estimated the neutral fraction of hydrogen $n_{H\ I}/n_H = 10^{-2.5}$. The number density of hydrogen is calculated from its relation to the ionization parameter, $U = n_\gamma/n_H$, where n_γ is the number density of photons with energies above one Rydberg. Using a background mean intensity of $J_\nu = 10^{-21}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}, and ionization parameter of $U = 10^{-3}$, we find $n_H \approx 0.005$ cm^{-3}. For QSO 1937−1009 the blue component with log N(H I) = 17.74 has $L = 11$ kpc, and the red component has log N(H I) = 17.50 and $L = 7$ kpc. For QSO 1009+2956 the blue component has log N(H I) = 17.36, $L = 5$ kpc and the red component has log N(H I) = 16.78 and $L = 1$ kpc. A characteristic thickness (along the line of sight) of our Lyman Limit systems is $L = 10$ kpc.

6.2 Mass probed by the quasar light

The total mass depends on the shape of the gas cloud. The mass in the line of sight is proportional to the volume of the cloud, $M = \rho\,\pi\,r^2\,L$, where $\rho = \mu\,n_H \approx 10^{-26}$ g cm^{-3} is the mass density of the gas, and r is the radius of the background light at the redshift of the absorption system. In both of our systems, emission redshifts $z_{em} - z_{abs} \ll 1$, so r is approximately the size of the optical radius of the QSO. We assume this radius to be $r = 1$ pc, and find $M \approx 5M_\odot$, for a thickness of $L = 10$ kpc.

This mass is a tiny fraction of the entire absorbing cloud, since the quasar

light probes a very narrow "pencil-beam" down the line of sight. Since absorption lines measure the total optical depth in this pencil-beam, any localized destruction of D will be insignificant to the total optical depth. This rules out destruction of D in stellar winds [12].

The total mass depends on the shape of the absorbing cloud. If they are spherical $M \approx 2 \times 10^9 M_\odot$ for a diameter of $L = 10$ kpc. If they are flat, then we will see more of those which are near face on, because they present a larger cross section, and because the D/H systems are biased to have simple velocity structure down the line of sight. The total masses of observed clouds will then average larger than the masses estimated assuming spherical shapes.

7 Destruction of D in stars

The ISM D/H is 0.67 ± 0.09 of the value which we measure. This implies that 0.33 of D is destroyed when the Oxygen abundance rises to about 0.3 of the solar value. If the destruction of D is proportional to metal abundance, then < 0.002 of D would be destroyed when the O abundance is < 0.003 of solar. This is conservative because the present ISM involves stars with a variety of masses. At early epochs destruction would mostly be by higher mass stars, (because low mass stars are still on the main sequence and have not ejected much matter) which eject more metals relative to H than do low mass stars. This gives less D destruction per metal atom added to the gas.

8 Comparison with other D/H Possible Detections in QSO Spectra

Table 2 lists the six absorption systems which might show D, along with a recent measurement of D in the ISM. Notice the wide range of D/H values. How can a single value for primordial D/H arise from values spanning a whole order of magnitude?

The values of D/H in the absorption systems should not be weighted equally. Our two values of D/H have statistical errors of 20% or less, while the other detections have errors greater than 50%. In regards to absolute sensitivity to D/H, our two measurements are 10 times more sensitive than the others. Ours are sensitive to D/H at 1 part in 10^5, while the others are only sensitive to D/H in parts to 10^4. We now compare the other measurements of D/H listed in Table 2 to our measurements.

Q0014+8118, $z_{abs} = 3.320$**:** The QAS towards Q0014+8118 differs from our two in several ways. Since no metal lines were detected, the velocity structure of the cloud could be determined only by median filtering of the higher-order lines in the Lyman-α forest [14], and the Lyman-α feature was considerably more complex: five components were required for an adequate fit

Table 2: Deuterium in QSO Spectra.

QSO	z_{abs}	D/H [a] (10^{-5})	N(H I) [b] (log)	[C/H][c]	Reference
ISM	0.0	1.6 ± 0.1	18.2	...	[9]
(A) 1009+2956	2.504	2.5 ± 0.5	17.46	-2.9	...
(B) 1937−1009	3.572	2.3 ± 0.3	17.94	-2.2, -3.0	...
(C) 0014+8118	3.320	≤ 25	16.7	< -3.5	[14, 3, 11]
(D) 0014+8118	2.798	19 ± 9	18.04	-2.5	[12]
(E) 1202−0725	4.672	≤ 15	16.7	...	[18]
(F) 0420−3851	3.086	≥ 2	≥ 18	-1.0	[4]
(G) 1422+2903	3.515	200 ± 70	15.25	...	

[a] We show the approximate 1σ random error.
[b] Column density in logarithmic units of cm^{-2}.
[c] Carbon to hydrogen ratio in logarithmic units, relative to solar.

([3]). The neutral hydrogen column density of the component where deuterium is measured, log N(H I) = 16.74, is 4 and 10 times lower than the column densities in our two QAS, which reduces the sensitivity to low D/H. The published fits to the D line are either poor [11], or require additional H on both sides of the line [3].

Q0014+8118, $z_{abs} = 2.798$**:** Rugers & Hogan (1996b) identify a second deuterium "feature" in the same Keck HIRES spectra. But the identification is not a feature, only the blue wing of a Lyman-α absorption complex. They model deuterium Lyman-α as saturated, giving a column density of log (D I) $= 14.31 \pm 0.25$. This absorption will be hard to confirm because Lyman-β is to the blue of the Lyman edge of the other absorber, where there is little flux. With only the wing of Lyman-α in low S/N spectra (S/N ≈ 20), and no higher order Lyman lines, we conclude that this identification of deuterium is far from certain.

Q1202-0725, $z_{abs} = 4.672$**:** Although the high redshift of this system should allow a measurement of D at earlier epochs, the density of Lyman-α lines significantly increases the chance of interlopers. In addition, this system may have a very high oxygen abundance, twice that of the sun [18]. The column density of N(H I) is poorly constrained, due to the low optical depth at the Lyman continuum and the contamination of higher order Lyman lines by the Lyman-α forest. The spectra have relatively low SNR, and the fit to D is

not tightly constrained. We conclude that this system is not well suited for a measurement of D/H.

Q0420-3851, $z_{abs} = 3.086$**:** This absorption system is very complex, over 9 components are required for an adequate fit. The lower S/N $\approx$ 10 spectra do not tightly constrain H I or D I. The metallicity is also high, approximately 1/10 of solar. The confusion associated with this system makes this a poor candidate for an accurate measurement of D/H.

9 What is the Cosmological D/H Value?

There are only three claims of a detection of D: our two and that by [14]. All others were first presented as upper limits, as was that by [14]. Our two D/H values agree, while the third is 10 times larger. There are three options:

1. The cosmological D/H is low, at the value which we see in two QSOs. The high values reported by others are all contaminated by H lines, and in many cases the SNR is too low to see D even if there was no contamination. We show below that this explanation provides a complete description of all D/H data.

2. The cosmological D/H is high, at the value suggested by [14]. Our data disagree with this high D/H at the 50 and 70 σ level, so D must have been destroyed by some unknown astrophysical process.

Rugers & Hogan (1996) speculate that winds from high mass stars might eject gas which lacks D and metals. This process is ruled out for three reasons. First, the absorbing clouds are about 10 kpc along the line of sight, but winds from individual stars will travel pc. We would need many stars, lined up along the line of sight. Second, these stars will explode and eject metals a short time after their winds eject H without D. We would need to synchronize the star formation along the 10 kpc line of sight, so that nearly all stars were in the stellar wind phase at the time of observation. And we would need to avoid high mass stars which explode shortly after they form. Third, we see identical D/H in two lines of sight. Towards QSO 1937−1009 we must remove 90% of the D, while towards QSO 1009+2956 we must remove 87%. Hogan agrees (private communication, May 1996) that this rules out their suggestion.

Hypothetical mechanisms which destroy D without making metals must also meet other constraints. They must not operate in the local interstellar medium (ISM), where D/H is approximately constant, and they must not take D/H to values lower than in the ISM, and they not change the C/Si abundance ratios which we measure to be the same as in Galactic halo stars.

For these reasons, we also disagree with Schramm & Turner [13] who stated "it may be that the cloud is very inhomogeneous and the heavy elements have

been dispersed. This is not implausible, because the material giving rise to the absorption lines has only a tiny fraction of the cloud's mass." The gas in QSO 1937−1009 is clearly inhomogeneous (the two clouds differ in z, metal abundance, T, and b_{tur}), but we do not see how metals can be removed from two lines of sight, each 10 kpc long, leaving the same D/H in each. The turbulence along both line of sight is subsonic, with very low bulk motions ($b_{tur} < 2$ – 8 km s^{-1}), and no sign of shocks. And where are the metals which have been ejected from the gas clouds? They should be seen. These absorption systems have high N(H I) and low metal abundances. If the metals were ejected, they should create high metal abundances in gas with low N(H I) (high N(H I) is very rare), which is not common. We would also expect that the metal, H and D lines would have different velocity profiles, but they are similar, especially for QSO 1009+2956 .

The observation of the same D/H in two lines of sight should rule out all unusual astrophysical effects, and all chance data glitches.

3. The universe is inhomogeneous and D/H is high in some places, and low in others. The natural mass scales for inhomogeneities in isocurvature fluctuations are compatible with the observations: 10^6 – 10^{11} solar masses [7]. But the mean cosmological D/H should be about 7×10^{-5}, higher than suggested by our two measurements. And we would expect to see a variety of D/H values, such that it might be hard to understand two values which agree to within 10% and a third which differs by a factor of ten. However more high quality measurements will be needed to determine if D/H varies spatially.

10 False Identifications

In Figure 5 we show Keck spectra of most of the Lyman-α forest of QSO 1946+7658. Note the extremely large number of lines, and especially the saturated lines which go to zero flux in their cores, as must all with enough N(H I) to show D. Any of these saturated lines might have enough N(H I) to show D; it is hard to tell because we must fit each line to find its N(H I). All saturated lines have log N(H I) $\geq$ 14.5, unless they happen to be a close blend of lines with lower N(H I). But most saturated lines have 0.001 – 0.01 of the N(H I) needed to show D. Lines suitable for D must have both high N(H I) and low b, so they are not necessarily the widest lines. This spectrum shows why we prefer to see the Lyman limit and metal lines, before we make a claim to a detection of D.

In Figure 6 we show a portion of the spectrum of one QSO which appears like D next to H. We spent 1 hour searching one spectrum to find this example. The fit with one component for D is poor, and should be rejected. The fit with

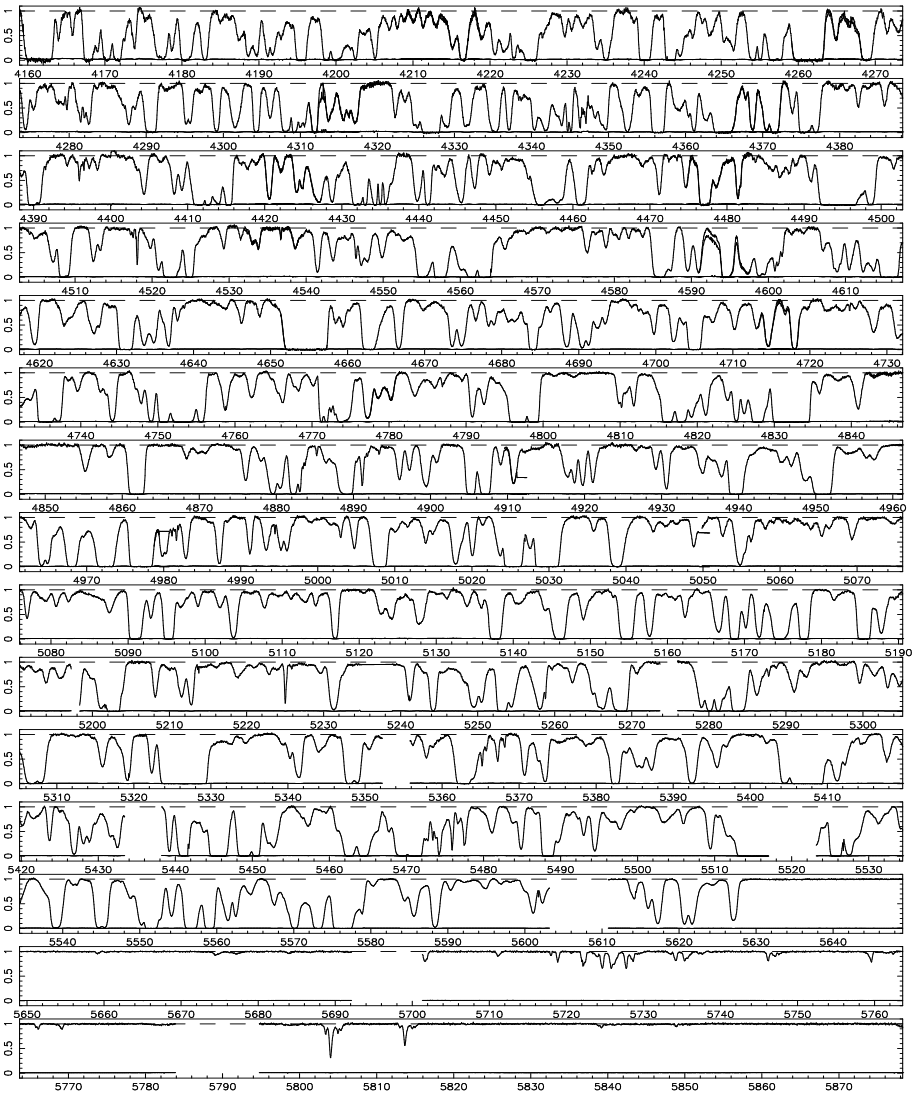

Figure 5: Keck HIRES spectrum of QSO 1946+7658 at 8 km s^{-1} resolution and SNR > 100 in many pixels. Most of the absorption lines are Lyman-α forest lines. Lines which have zero flux in their centers are saturated, and about one of these lines might have enough N(H I) to show D, if it also had a low velocity dispersion. The last two panels cover wavelengths outside the Lyman-α forest, where there are no H I lines, because $\lambda > 1216 \times z_{em}$.

two components (Figure 7) looks excellent, and gives $D/H = 2.1 \pm 0.7 \times 10^{-3}$. We do not think this is D, because such chance occurrences of a weak H line just to the blue of a strong saturated line are common, and examples can be seen in Figure 5. This explains why Rugan & Hogan are able to find two examples of D/H in the Keck spectrum of one QSO, where as we believe that D is seen in about 3% of QSOs.

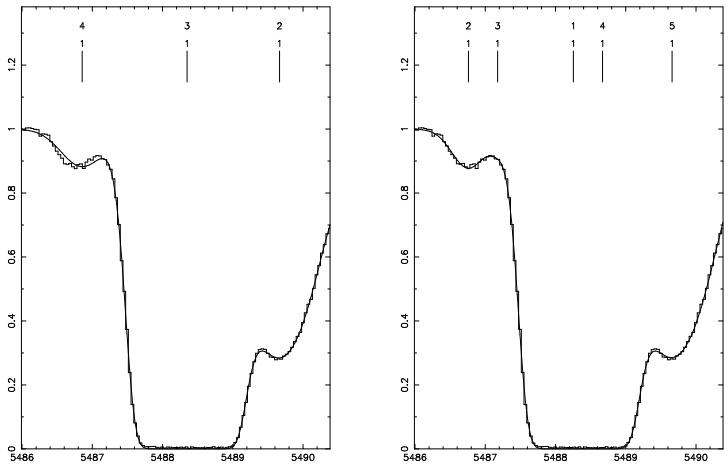

Figure 6: Keck HIRES spectrum of QSO 1422+2309 with SNR 100 per pixel. The fit on the left used only one H component to fit the saturated absorption line and one component to fit the correspsonding D line. The fit is poor, and rejected. The fit on the right has two critical components for H (11 and 41) and D (21, 31). This fit looks much better, and gives an extremely large D/H, but we do not accept it as a D/H measurement, because there is a large chance that the D line is H, for the following reasons, which are explained in the text. (1) There is no supporting evidence [metal lines for z values, predictions for b(D), estimates of temperature, or element abundances which would indicate that the fit is reasonable]. (2) We required two components to fit D. These were determined *ad hoc* to get a fit to D and H, without additional evidence. (3) N(H I) is low. (4) We searched only one QSO for this example. (5) The fit is actually poor with a reduced $\chi^2 = 4.1$ per degree of freedom over 114 pixels, which is hard to see because the SNR is so high. We reject this as D/H even though there are some favorable characteristics: (6) The SNR is very high, 100 per pixel. (7) The spectral resolution is excellent, 8 km s^{-1}. (8) The D line is clearly resolved from H. (9) There is no doubt that there is a feature at the position of D. In these respects this D/H candidate is better than most of those in the literature.

10.1 Fits should be excellent and unique

The higher the SNR of the data, the harder it is to get an acceptable fit, because we see the details of the velocity distribution of the absorbing gas. Fits must

be excellent in the regions of the spectrum where one fit is distinguished from another with very different D/H. It is not sufficient that a fit have a reasonable χ^2 over the whole line. The χ^2 must be good over just those pixels which are critical to the fit. Inclusion of additional pixels increases the number of degrees of freedom, and can hide a fit which is poor in the critical regions.

Two of the published fits to QSO 0014+8118 are unacceptable, while the third is not unique because it has too many free parameters. Songaila et al.[14] show a D line which is much too narrow to account for observed absorption (their Fig 3). Additional absorption, probably H, is required on both sides of the line, as was shown by Carswell et al. [3] (their Fig 2). This fit is good, but it is not unique because they must introduce 6 new free parameters (3 per new H line) to fit the region which could contain D. There extra parameters greatly increase the chance that the line is almost entirely H.

Rugers & Hogan[11] reanalyzed the published spectra of Q0014+8118, and determined that the deuterium feature is better fit with two very narrow components separated by 21 km s^{-1}. Their model is unphysical, because it absorbs flux at wavelengths where flux is seen: e.g. in the Lyman lines at 3974, 3972, 3962.5, 3961, 3959.5, and 3954.8 Å (their fig 2). The fit is also poor in other places: D I Lyman-α , H I Lyman-γ and Lyman-δ blue wing and central spike. It is especially unfortunate that the fit is bad right in the center of D at 5251 Å, where the data shows a spike where there model specifies there should be none (their fig 1). This is the critical part of the spectrum, which determines if there is one or two components to D. It seems that these components were chosen ad hoc to fit the hypothesis that the line was D: they do not fit the data, and they are not motivated by other lines. For our two QSOs the two components are required by metal lines.

The Rugers & Hogan[12] fit to a second D/H candidate in the same QSO (0014+8118) is not acceptable because it is not unique. Here the blue edge of a completely saturated line is assigned to D, while the rest of the line is composed of 7 additional components which were seen in metal lines. It seems more likely that the D line is another H line. There is no reason to suppose that this is D.

10.2 Ideal Systems

The chances of false identification of a pair of H lines as D and H is reduced in the following circumstances.

Search Many QSOs

It is best to search many QSOs and concentrate on the best few systems. The chance of a false identification increases greatly when a lot of attention is spent looking for any features which might be D/H in a few spectra. We find it amazing that Hogan & Ruger's have found two cases of D in one spectrum, when we have 2 from about 77 QSOs.

Give preference to high H I column densities.

There are three reasons why false identifications will be rarer when N(H I) is as large as possible. First, systems with large N(H I) are rare, so they will give fewer false identifications per QSO. Second, larger N(H I) means larger N(D I) for a given D/H. This reduces the chance that the D line is H, because the contaminating H would need a large N(H I), which is rare. Third, if N(H I) $\lesssim 10^{17}\mathrm{cm}^{-2}$ then the D line will be too weak to see in even the best Keck spectra for D/H $\simeq 2.4 \times 10^{-5}$. In such cases all features which look like D/H must be false identifications.

In all three cases, the chance of false identification of an H line as D will increase in data with lower SNR and/or lower spectral resolution, because we have less signal to distinguish D from H.

Use Metal lines to Constrain Velocity Structure.

Ideally metal lines should be used to determine the velocity structure of the absorption system. The metal lines show the redshifts z of the absorbing clouds, and both the turbulent velocity dispersions b_{tur} and temperatures T of the gas in each cloud. These metal line parameters specify the profile of the D line, except for D/H and possible additional absorption by other ions, especially H. Our two QSOs are the only ones for which the profile of D has been fixed by metal lines.

There must be both H and D at all redshifts seen in metal lines, because we do not know how to remove all H and D from gas which contains only heavier elements and is distributed over kpc. The fit to the H and D lines must contain gas at the redshifts given by the metal lines, and this greatly reduces the chance of false identification of a random H line as D. Without metal lines, there are far more velocities at which we could place the H and D lines.

It is always possible that the amount of H near the D line is sufficient to require extra components in the fit. This additional gas decreases the confidence in the identification of D, because it broadens the D line, making it look more

like an H line, and it adds 3 degrees of freedom (z, b & N) per component, which again increases the chance that the whole D lines is dominated by H. For our two QSOs the D feature is completely fit by the clouds seen in the metal lines, but for the system in Q0014+8118 [14] additional H or D is required.

11 Check List for Reliable D/H Measurements

We summarize and conclude this discussion of the measurement of D/H in QSO spectra with a list of some of the questions which we ask when we try to decide if a measurement is reliable and accurate.

The data:

1. How many QSOs were searched to find the D/H value? There is more chance of a false identification if only a few spectra were studied, because systems which give secure D/H are very rare.

2. Was there a systematic search for D in the spectra of many QSOs? What criteria were used to select QSOs for detailed observation?

3. The SNR should be high: $\simeq 100$ per 0.04Å is excellent. Lower SNR increases the chance that the D feature is contaminated with H.

4. The spectral resolution should be high: 8 km s^{-1}FWHM is excellent. Lower resolution increases the chance that the D feature is contaminated with H.

The absorption system:

5. How large is N(H I)? Count only the gas which shows D. High values are much more likely to give a real D detection. If log N(H I) $\lesssim 10^{17}$ we are unlikely to detect D/H $\simeq 2 \times 10^{-5}$ with the best Keck data. If D/H is low, every claim of D in a system with low N(H I) must be contaminated.

6. How well is N(H I) determined? If from a Lyman limit alone, is it know that there are no other systems which could account for the Lyman continuum absorption? If from Lyman line, the more lines the better. One saturated line is inadequate in low SNR data, but may be acceptable with high SNR and high resolution. Ideally N(H I) is from many Lyman lines and the Lyman continuum.

7. How certain is it that there is a feature at the position of D?

8. How was the position of D determined? If from the D line itself, then there is a large chance of H contamination. Ideally from metal lines and narrow high order Lyman lines.

9. How many components were required to fit D? The fewer the better.

10. Are additional H components needed to fit around D? This is bad and increases the chance of contamination.

Table 3: Reliability of D/H Measurements in QSO Spectra.

Criterion	Deuterium (A)	(B)	(C)	System (D)	(E)	(F)	(G)
Many QSOs searched?	7	7	3	3	3	3	0
Systematic D/H search?	10	10	2	0	0	0	0
High SNR?	5	8	4	4	3	2	9
High spectral resolution?	10	10	10	10	5	5	10
High N(H I)?	6	8	2	8	2	10	0
Small σ for N(H I)?	6	7	8	2	7	0	4
Definite feature at D?	10	10	7	0	7	0	10
D v from other ions?	10	10	10	8	7	10	0
Few components to fit D?	5	5	3	0	10	0	5
Extra H to fit D?	0	0	-5	0	0	-5	0
Component v from where?	10	10	5	10	0	0	0
How good is fit to data?	10	10	5	2	5	8	10
Is fit unique?	0	0	0	-5	0	-5	0
Is b(D) known?	5	5	7	5	0	5	5
Was b(D) predicted?	7	7	0	7	0	5	0
Agreement on b(D)?	7	7	0	7	0	3	0
Metal abundance low?	10	10	10	7	0	5	0
Additional evidence?	5	5	0	0	0	5	0
H contamination corrected?	10	10	0	0	0	0	0
Total (out of 170)	133	139	71	58	49	51	53

11. How were the velocities of the components determined? If from D, then there is a high chance of contamination. Ideally from metal lines and narrow high order Lyman lines.

12. How good is the fit? It must be excellent in the critical regions which distinguish different values of D/H.

13. Is the fit unique? Do different fits give different D/H?

14. Was the b value of D measured? If not, why not? Lack of a measurement is a sign of a non-unique fit, poor data, or strong blending, all of which favor contamination by H.

15. Was the b value of D predicted? Whenever metal lines are seen the

temperature and b_{tur} should be measured and used to give a prediction. If b is not measured, then b should lie between b(H) and b(H)/$\sqrt{2}$. Gas which is suitable for the detection of D will be cool, and will have low b_{tur}, but thermal motions will probably dominate the b values of D and H.

16. How tight is the agreement between the predicted and measured b(D)?

17. Was the metal abundance measured? If not, why not? It could be high.

18. Is there additional evidence that the fit to the system is reasonable, such as standard element abundance ratios and reasonable temperatures (few 10^4 for ionized gas)?

The analysis:

19. Was there a Monte Carlo correction for Lyman-α forest lines at the position of D. If not, why not? Such corrections are hard to make when fits are poor or ambiguous.

In Table 3 we include subjective estimates of how well each absorption system (see Table 2) performs on the 19 questions. We assign a score of 10 for an excellent indication of good D/H, zero for no information, and negative numbers for problems which make D/H uncertain. Questions 19 is the key, since it summarizes the probability that the D line is contaminated. The two absorption systems discussed in this paper are the only ones to pass all of these tests. The others fail many tests, and for this reason they are likely to be strongly contaminated by hydrogen. Note that the absorption in QSO 1422+2309 (G), which we think is completely contaminated with H, ranks as well or better than many others.

12 Acknowledgments

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